Simplified Models for Mask Roughness Induced LER

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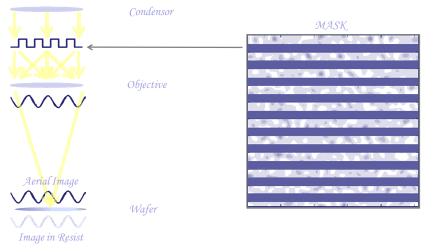
An issue requiring some attention

The ITRS requires < 1.2nm line-edge roughness (LER) for the 22nm half-pitch node. Currently, we can consistently achieve only about 3nm LER. Further progress requires understanding the principle causes of LER.

Much work has already been done on how both the resist and LER on the mask effect the final printed LER. What is poorly understood, however, is the extent to which system-level effects such as mask surface roughness, illumination conditions, and defocus couple to speckle at the image plane, and factor into LER limits.



A typical lithography system, Kohler Illumination.

Presently, mask-roughness induced LER is studied via full 2D aerial image modeling and subsequent analysis of the resulting image. This method is time consuming and cumbersome.

It is, therefore, the goal of this research to develop a useful "rule-of-thumb" analytic model for mask roughness induced LER to expedite learning and understanding.

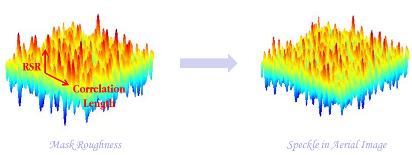
Mask Roughness LER: Random or Predictable Effect?

When coherently illuminated, roughness on the mask couples to speckle in the aerial image. By specifying illumination conditions (coherence, σ), optical conditions, and mask roughness characteristics (replicated surface roughness (RSR) and correlation length), the resulting speckle statistics are largely determined.

$$Speckle = \partial I$$

Intensity variations, specified by illumination conditions and mask roughness parameters

Greater height variations (RSR) and lesser self-similarity across the mask (correlation length) mean that the mask is "rougher" in a statistical sense.



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So…Can't we push a few terms around and rearrange?

$$LER = 3\sigma = 3 \cdot Speckle \frac{1}{Intensity \cdot ILS}$$

A Simplified Solution

Given the rms speckle (intensity variation), the resulting LER can be expressed in terms of the aerial image log slope (ILS). In practice, the ILS can be quickly determined using 1D aerial image simulations. To determine the illumination- and mask-specific clear-field rms speckle, a one-time 2D aerial image simulation can be performed, and the speckle is scaled by the intensity. From these two values, the full parameter space can be reached by this analytic extension.

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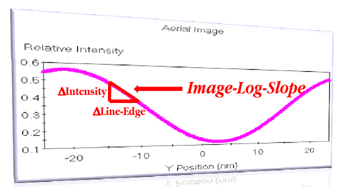
Image-log-slope (ILS) measures the aerial image intensity transition across an edge when features are present on a mask; e.g. from line to space.



ILS is typically used as a metric of imaging quality, and can be applied to determine the coupling from intensity variations (speckle) to line-edge movement (LER).

$$ILS = \frac{\partial \ln I}{\partial x} = \frac{1}{I}\frac{\partial I}{\partial x}$$

small change in intensity

movement of line-edge

2

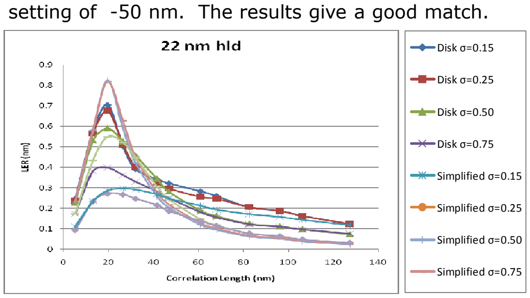
Larger ILS means that a given intensity variation would change line-edge position *less* than a smaller ILS would.

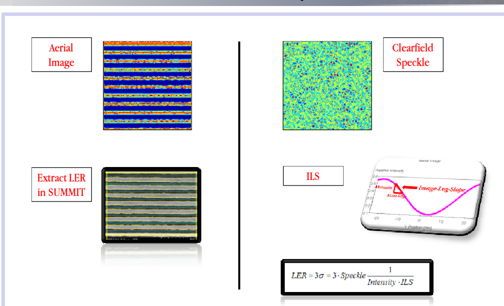
Verification — Simulated = Simplified?

To verify the validity of this approach, we compared the analytic LER to the LER resulting from the full 2D aerial image simulations (extracted using SUMMIT).

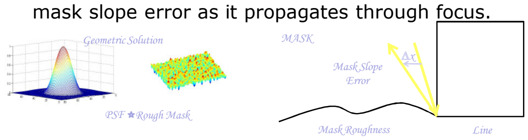
Data was based on an imaging system with objective NA = 0.5, RSR 50 pm and 230 pm, four disk illumination settings (σ = 0.15, 0.25, 0.50, 0.75), for 22 nm, 40 nm, and 50 nm lines and spaces, for a variety of correlation lengths (5, 13, 20, 26, 32, 42, 47, 61, 68, 83, 96, 106, 127 nm).

Plotted below are the 22 nm lines and spaces, RSR 50 pm, through correlation length at one defocus setting of -50 nm. The results give a good match.



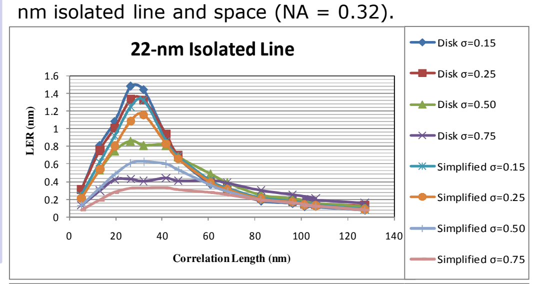


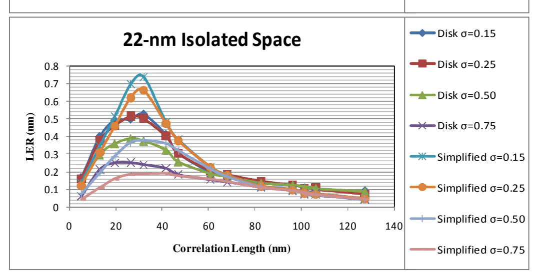
For large RSR and long correlation lengths under highly coherent illumination, the LER enters a "geometric regime", whereby it is proportional to the mask slope error as it propagates through focus.



To confirm, we convolved the PSF of our optical system with the clear-field rough mask, took the slope, and propagated through focus appropriately.

The geometric model gives an excellent match. The results below show that the model works well for 22 nm isolated line and space (NA = 0.32).





a rule-of-thumb

A simplified solution exists for mask roughness induced LER. It provides a powerful, fast method to obtain LER. Data shows that to meet ITRS specs for the 22-nm half-pitch node, an RSR of 50 pm and correlation length greater than 50 nm will be required for the NA = 0.5 imaging system.

For correlation lengths greater than 3λ/NA in wafer dim. and CDs greater than approximately 0.75λ/NA, the simplified model which remains based on wave optics converges to a "geometric regime" which is based on ray optics and is independent of partial coherence.

In this "geometric regime", the LER is proportional to the mask slope error as it propagates through focus, and provides a faster alternative to calculating LER in contrast to either full 2D aerial image simulation modeling or the newly proposed simplified model.

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